Stellar Reactions with Short-Lived Nuclei: ^{17}F$(p,\alpha)^{14}$O

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A method has been developed that can provide beams of many short-lived nuclei of interest in nucleosynthesis along the rp process path. With a ^{17}F beam ($T_{1/2} = 64$ s) the excitation function of the ^{17}F$(p,\alpha)^{14}$O reaction was measured to determine properties of excited states in ^{18}Ne. These states influence the rate of the ^{14}O$(\alpha,p)^{17}$F reaction which is important for understanding energy generation and nucleosynthesis in x-ray bursts. The present direct measurements yield a pattern of resonances and cross sections which differ substantially from previous estimates. [S0031-9007(99)09166-8]

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Reactions involving short-lived nuclei play an important role in nuclear astrophysics. In explosive astrophysical events, such as x-ray bursts, novas, or supernovas, the reactions occur on a sufficiently fast time scale that the reaction products on the proton-rich side of the valley of stability, that normally decay through the weak interaction, instead interact further with the protons and alpha particles which are present in the dense and hot stellar environment. To study these reactions a method has been developed for producing beams of such short-lived nuclei that can be reached by either (p,n) or (d,n) reactions from stable nuclei. This report describes the production of a ^{17}F beam ($T_{1/2} = 64$ s) and the first measurement of the ^{17}F$(p,\alpha)^{14}$O reaction.

X-ray bursts [1–3] may be an important source for the production of proton-rich nuclei via the high temperature rp process [4]. These events initially produce a large abundance of ^{14}O when the triple-alpha process is ignited at a temperature of $\sim 2 \times 10^8$ K, but the peak energy generation rate is not achieved until, at much higher temperatures, the ^{14}O bottleneck is broken. Measurements of waiting point reactions such as ^{14}O$(\alpha,p)^{17}$F are thus important for understanding the details of energy generation and nucleosynthesis in these stellar environments.

Prior to the present measurements, estimates of the absolute value and energy dependence of the ^{14}O$(\alpha,p)^{17}$F cross section had been made from indirect information. Since the reaction is mainly resonant, it depends on the properties of unbound states in the compound nucleus ^{18}Ne. The properties of these levels had been inferred [5–9] by measuring the resonance energies with other reactions and by estimating widths and spin assignments from the mirror nucleus ^{18}O, utilizing isospin symmetry with appropriate Coulomb shifts. The ^{14}O$(\alpha,p)^{17}$F reaction rate at lower temperatures is believed to be dominated by a resonance arising from a 1^- state that is the isobaric analog of the $E_x = 6.20$ MeV state in ^{18}O. This level has been tentatively identified with a state at $E_x = 6.15$ MeV in ^{18}Ne [5]. Several states at $E_x = 7–7.5$ MeV may also contribute to the reaction rate at higher temperatures (up to $\sim 3 \times 10^9$ K) relevant for x-ray bursts. The goal of the present work was to determine the properties of states in ^{18}Ne that may contribute to the ^{14}O$(\alpha,p)^{17}$F reaction rate by measuring the excitation function for the time-inverse ^{17}F$(p,\alpha)^{14}$O reaction.

The ^{17}F beam was produced using an in-flight technique similar to the ones described in Refs. [10–12]. In this experiment, a primary beam of ^{16}O was used to produce a ^{17}F secondary beam via the $d(^{16}\mathrm{O},^{17}\mathrm{F})n$ reaction. A liquid-nitrogen cooled, 3.5 cm long gas cell target, filled with $\approx$0.8 atm of D_2 gas was bombarded with an ^{16}O beam of $\sim$100 pnA (6×10^{11}/s) at energies

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between 70 and 90 MeV from the ATLAS accelerator at Argonne National Laboratory. The ^{17}F ions left the gas cell in a 5° cone with respect to the primary beam direction, with a total energy spread of ~20 MeV. A superconducting solenoid refocused the ^{17}F particles, and superconducting resonators before and after the gas cell reduced the energy spread of the beam. The $^{17}F^{+9}$ ions were separated from the ^{16}O beam in a bending magnet and refocused onto a 5×5 mm^2 beam spot, with an energy spread less than 500 keV. Between 2×10^5 and 2×10^6 particles/s were incident on the target. The (lower energy) ^{16}O contamination was between 10% and 50% and did not interfere with the measurement. Details of the production, transport, and beam monitoring scheme are given elsewhere [12,13].

The $p(^{17}\mathrm{F}, \alpha)^{14}\mathrm{O}$ reaction was measured at a number of incident energies, using several CH_2 targets with thicknesses of ~100 or ~500 μg/cm^2. Each measurement represents an average over the energy loss in the target which corresponds to 0.7(3) MeV in laboratory energy, and 40(170) keV in the center-of-mass system. Two position sensitive, double-sided, annular silicon strip detectors behind the target were used to measure the energy and angle of the scattered particles. Coplanar kinematic coincidences were required between the α particle in the first detector, covering the angular range ~13°–25°, and the ^{14}O residual nucleus in the second detector at angles ~4°–8°.

Figure 1a shows a plot of the energy of the α particles vs the energy of the coincident ^{14}O partners. The background seen below the line of constant sum energy is attributed to reactions of the beam with ^{12}C in the CH_2 target. Shown in Fig. 1b are the ^{14}O-α coincidence events as a plot of ring number (scattering angle θ_α) vs α energy, gated by the "good" events in the E_α-$E_{^{14}\mathrm{O}}$ plot, with the requirement of coplanarity. The solid lines in Fig. 1 indicate the expected kinematic behavior for the reaction with the average energy loss of the real target.

The measured total cross sections are presented in Fig. 2 as a function of the center-of-mass energies in both channels. The uncertainties in the cross-section values shown are statistical. The detection efficiency was ~65%, obtained from a Monte Carlo calculation assuming an isotropic angular distribution, and including the effects of a finite beam spot and multiple scattering in the target. The integrated beam intensity was obtained from the ^{17}F ions scattered by ^{12}C in the target. Only events with $\theta_{\mathrm{lab}} < 6°$ were used in this procedure, to assure the dominance of Rutherford scattering.

The energy intervals covered by the thin or thick targets (circles or crosses) are indicated in the figure by the horizontal lines. The total systematic uncertainties are estimated to be ~20%. The results of the thin- and thick-target measurements are consistent within statistical errors.

Previous estimates of the $^{14}\mathrm{O}(\alpha, p)^{17}\mathrm{F}$ reaction cross section [5–9] utilized the known levels of ^{18}O to obtain assignments to states in ^{18}Ne with $E_x > 5$ MeV. The energies of the unbound levels in ^{18}Ne were obtained from the $^{20}\mathrm{Ne}(p,t)^{18}\mathrm{Ne}$, $^{16}\mathrm{O}(^3\mathrm{He}, n)^{18}\mathrm{Ne}$, and $^{12}\mathrm{C}(^{12}\mathrm{C}, ^6\mathrm{He})^{18}\mathrm{Ne}$ reactions [5,6]. The cross section, in the energy interval covered here, for the $^{14}\mathrm{O}(\alpha, p)^{17}\mathrm{F}$, and thus for the $p(^{17}\mathrm{F}, ^{14}\mathrm{O})\alpha$, reaction is dominated by resonant contributions from levels at $E_x = 6$–8 MeV in ^{18}Ne. In Ref. [5], the partial widths of resonances were taken either from the known widths of the corresponding ^{18}O levels or were assumed to have spectroscopic factors which are typical in this region of nuclei. A comparison of the results of this estimate (see solid and dotted lines in Fig. 2) with our data shows distinct discrepancies. In the present experiment three resonances were observed at excitation energies of 7.60 ± 0.05 MeV, 7.37 ± 0.06 MeV, and 7.16 ± 0.15 MeV. These energies are consistent with previously observed states in ^{18}Ne; however, the strengths of these resonances differ substantially from earlier estimates [5]. The current results are summarized and compared to previous results in Table I and in Fig. 2. Since the proton widths in this energy region are generally much larger than the alpha widths, the resonance strength can be approximated by $\omega\gamma = \omega\Gamma_\alpha\Gamma_p/\Gamma_{tot} \approx \omega\Gamma_\alpha$, where ω is the statistical factor from the spins involved.

A strong resonance was observed at 7.60 MeV in both the thin and the thick target measurements with a resonance strength of $\omega\gamma = (300 \pm 40)$ eV. In the energy range $E_x = 7.3$–7.5 MeV, the thin-target data show a possible small structure that is attributed to a weak resonance. Assuming a single level, a value of $\omega\gamma = (23 \pm 12)$ eV is obtained for this resonance. Another factor-of-3 increase in the thick-target yield is observed at $E_{\mathrm{c.m.}}(^{17}\mathrm{F} + p) = 3.06$ and 3.24 MeV. Assuming again a single level, this suggests an additional resonance at an excitation energy of ~7.16 MeV with $\omega\gamma = (75 \pm 20)$ eV. The yield measured at the lowest energy with the thick target is about a factor of 2 larger than expected from an estimate of the direct capture cross section [9]. This might conceivably be yet another resonance around $E_x = 7$ MeV or alternatively a direct contribution about twice as large as the theoretical estimate.

Cross sections have also been measured at c.m. energies between 2.2 and 2.5 MeV, corresponding to excitation energies of 6.1–6.3 MeV, where the 1^- state that is dominating the reaction rate is expected [5]. Some yield (~10–30 μb) was observed at the lower energies, while above 2.3 MeV only upper limits for the cross sections could be set. Although differences between measured and predicted cross sections are observed, the yields in this energy region are too small to allow a conclusive identification of the important 1^- state.

The difference between the observed and expected cross sections [5] is in part due to incorrect spin-parity assignments for particle-unbound states in ^{18}Ne. Some restrictions on the spin-parity assignments in ^{18}Ne can be made by comparing the present data with the corresponding well studied region of excitation energy in ^{18}O [14]. Considering ^{16}O as the core, the energy difference between

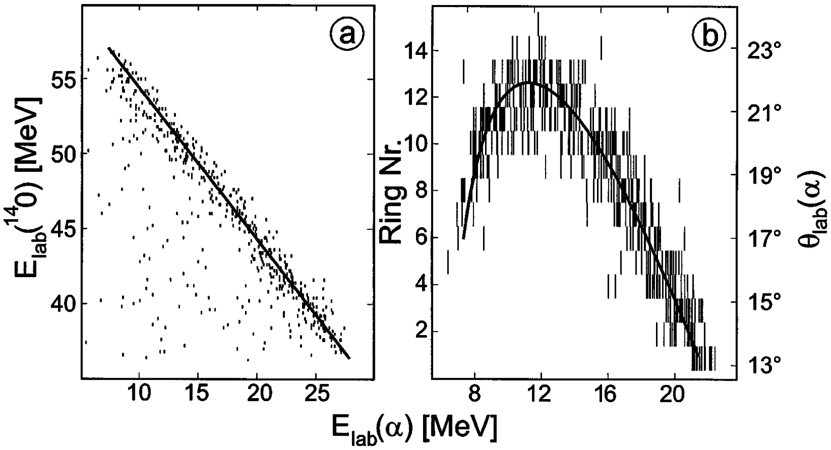

FIG. 1. (a) Energies of coincident α and ^{14}O particles. The coplanarity condition has been applied. (b) A two-dimensional scatter plot of α-particle angle (ring number) vs α energy for the events from (a), requiring also the correct sum energy. The solid lines represent the expected $E_\alpha - E_{^{14}\mathrm{O}}$ and $\theta_\alpha - E_\alpha$ correlations, respectively, for events originating from the midpoint of the target.

single neutron and proton states can be estimated from the $A = 17$ mirror levels that are well known [14]. While the total binding energies of the $5/2^+$ ground states of ^{17}F and ^{17}O differ by 3.54 MeV, those of the $1/2^+$ excited states differ only by 3.17 MeV, a 376 keV difference. This arises from the diffuse wave function of the loosely bound s-wave proton, and its lower Coulomb energy. The differences in excitation energies between corresponding states in ^{18}O and ^{18}Ne should then arise primarily from the amount of $s_{1/2}$ admixtures in their wave functions. Since the difference in isospin is two units, the shifts could be as high as ~800 keV. Since the ground state of ^{18}O has approximately a 15% $s_{1/2}$ admixture [14], the fluctuations of excitation energies of mirror states in ^{18}O and ^{18}Ne should be limited to $-250\ \mathrm{keV} < E_x(^{18}\mathrm{O}) - E_x(^{18}\mathrm{Ne}) < 800\ \mathrm{keV}$.

The parameters for the resonances found in the present work are summarized in Table I, which also includes the parameters used in Refs. [5,6]. The possible spin-parity assignments have been restricted by the limits on energy differences given above. The remaining options and constraints from the known widths of some of the levels in ^{18}O are also shown in Table I. By isospin symmetry, the reduced α-particle widths for the decay of excited levels in ^{18}O should be the same as the widths for alpha emission from the corresponding levels in ^{18}Ne.

With these criteria, the 3.24 MeV ($E_x = 7.16$ MeV) resonance in ^{18}Ne is consistent only with a 1^- assignment, and corresponds to the 7.62 MeV, 1^- level in ^{18}O. The 3.48 MeV ($E_x = 7.37$ MeV) level can be assigned either a 1^- or a 4^+ value. With the first assignment, this state would be the partner of the 8.04 MeV 1^- level in ^{18}O, with a Coulomb energy difference near the limit. The 4^+ assignment would make the state the partner of the 7.13 MeV 4^+ level in ^{18}O with the widths in rather good agreement. Finally, the strong 3.69 MeV ($E_x = 7.60$ MeV) resonance could have $J^\pi = 1^-, 2^+$, or 3^-. A $J^\pi = 3^-$ assignment, however, agrees poorly with the α width of the corresponding state in ^{18}O. Since there are only two

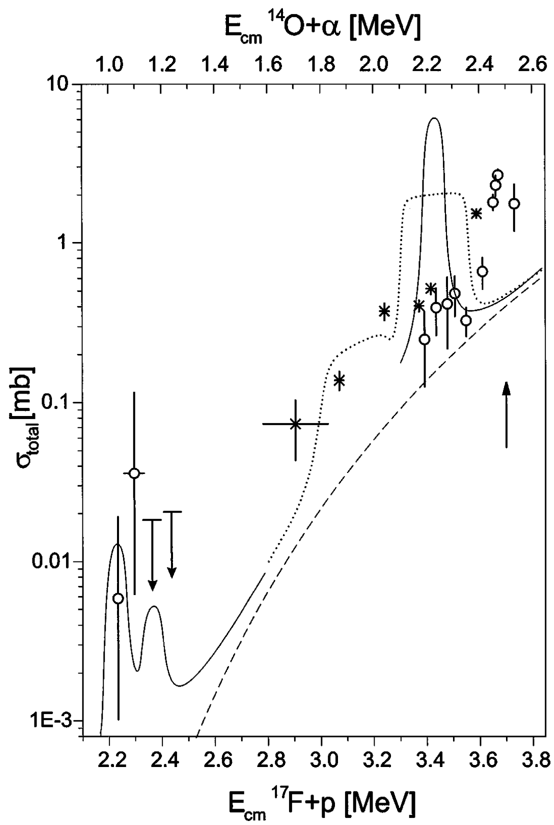

FIG. 2. Measured cross sections for the $p(^{17}\mathrm{F}, ^{14}\mathrm{O})\alpha$ reaction (top). The circles represent measurements with thin (100 μg/cm^2) targets, while the crosses are for thicker (500 μg/cm^2) ones. The horizontal bars, *shown for one point only*, indicate the energy interval corresponding to the target thickness. The dotted line represents the expected thick-target yield and the solid line that for the thinner targets using the resonance parameters of [5]. The dashed line is the direct component estimated in [9]. The arrow indicates the location of a state in ^{18}Ne that was listed in Ref. [5], but not included in the estimates. The energy scales at the top and bottom are for the entrance and exit channels involved in the reaction.

TABLE I. Resonance parameters for various states in ^{18}Ne. The first three rows are from the present experiment, while the last six lines were taken from Ref. [5].

E_x (^{18}Ne) [MeV]	$E_{\mathrm{c.m.}}$ (p,α) [MeV]	$\omega\gamma$ (p,α) [eV]	J^π	$\Gamma_\alpha^{\mathrm{expt.}}$ [keV]	Θ_α^2 (^{18}Ne)	E_x (^{18}O) [MeV]	Θ_α^2 (^{18}O)	$E_x(^{18}\mathrm{O})-E_x(^{18}\mathrm{Ne})$ [keV]
7.16 ± 0.15	3.24	75 ± 20	1^-	0.3	0.016	7.62	0.012[a]	460
7.37 ± 0.06	3.48	23 ± 12	1^-	0.08	0.002	8.04	<0.1[b]	670
			4^+	0.03	0.09	7.11	0.11[a]	−250
7.60 ± 0.05	3.69	300 ± 40	1^-	1.2	0.015	8.04	<0.03[b]	440
			2^+	0.7	0.026	8.21	0.03 ± 0.02[c]	610
			3^-	0.5	0.09	8.28	0.72 ± 0.04[c]	680
6.15	2.23	0.55	(1^-)	2.2×10^{-3}		(6.20)		
6.29	2.36	0.2	(3^-)	3.4×10^{-4}		(6.40)		
7.05	3.13	36	(4^+)	4.8×10^{-2}		(7.11)		
7.12	3.20	...	...	...				
7.35	3.43	375	(1^-)	1.7		(7.62)		
7.62	3.70	...	...	...				

[a] [15]. [b] [14]. [c] [16].

1^- states known in ^{18}O in this energy region, assignments of J^π for the observed resonances at 7.16, 7.37, and 7.60 MeV can be $(1^-;4^+;1^-)$, $(1^-;4^+;2^+)$, or $(1^-;1^-;2^+)$.

The contribution of these resonances to the $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ astrophysical reaction rate in the temperature range $T_9 = 1-3$ is found to be about a factor of 2 less than previous predictions. However, these measurements still leave open the question of the partial widths for proton decay to the $1/2^+$ excited state in ^{17}F in the $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ reaction, since the decay to that state would also contribute to the astrophysical yield. Future experiments which are optimized for measuring these proton widths will have to address this question.

The present experiment has shown that beams of short-lived, radioactive nuclei can be produced with the in-flight technique with energy resolutions of about 30 keV in the c.m. system. With a ^{17}F beam, a direct measurement of an excitation function of the $^{17}\mathrm{F}(p,\alpha)^{14}\mathrm{O}$ reaction has been performed, which is dominated by resonant states in ^{18}Ne. The measured cross section was found to differ substantially from predictions based on indirect measurements. The results of this experiment illustrate that the cross section estimates for astrophysical processes based on indirect methods are likely to be uncertain. As was found both here and in the $^{18}\mathrm{F}(p,\alpha)$ reaction [17,18], direct measurements of these cross sections are necessary to obtain good quantitative knowledge of the reaction cross section, even for nuclei as near to stability as in the present case.

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